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ANALYSIS OF ONBOARD RANGE-RATE SENSOR MEASUREMENTS FOR INTERPLANETARY NAVIGATION

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Advanced Mission Design Branch

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FIGURES

ANALYSIS OF ONBOARD RANGE-RATE SENSOR MEASUREMENTS FOR INTERPLANETARY NAVIGATION

By Flora B. Lowes

SUMMARY

A study to analyze the effects of a range-rate sensor measurement for onboard navigation during interplanetary flights is presented. The type of range-rate sensor measurement investigated is the sun line-of-sight rate of change. The effectiveness of this measurement is compared to that of an onboard planet-star included angle measurement with a sextant.

The results of the study indicate that an onboard range-rate sensor measurement of the type investigated is very effective in reducing spacecraft state uncertainties during the heliocentric phase of an interplanetary mission. However, the sextant measurement is better for onboard navigation when the spacecraft is within the sphere of influence of an observable planet. Several different errors were assigned to the range-rate sensor model for this study in order to better evaluate this type of measurement under various conditions. By doing so, it was shown that the range-rate sensor measurement is still significantly effective in the heliocentric phase of the trajectory even when assigned rather conservative errors.

INTRODUCTION

During the heliocentric phase (i.e., the trajectory phase in which the sun is the central body of the conic) of an interplanetary mission the geometrical configuration of the spacecraft's trajectory with respect to the sun changes very slowly. Thus, during this period onboard optical measurements made with a sextant or a theodolite involving the sun as a sighting body do very little in reducing uncertainties in the estimated state of the spacecraft. Also during the greater part of the heliocentric phase, the spacecraft is too far from any of the planets for measurements utilizing any of these to be of much significance.

Presently being considered is the development of a type of instrument which measures the rate of change of the line of sight to the sun from onboard the spacecraft. Thus, the study presented was undertaken to investigate the effectiveness of such a measurement in reducing spacecraft state uncertainties and, consequently, to determine the practicability of this type instrument for onboard navigation. The purpose of this paper is to present the analysis and results of a study of this range-rate sensor measurement. The digital computer program described in reference 1 was used to simulate the dynamics of the problem, as well as to process the measurements using a Kalman filter.

Because navigation studies using the sextant for the navigation measurements have been made for the 1975 Mars mission, data was readily available for comparison to data produced by the range-rate sensor navigation measurements. Thus, this particular Mars mission was chosen for the study.

ANALYSIS

The Mars flyby mission used for the study has a launch date of September 20, 1975 and an Earth injection velocity of 15 150 fps. This trajectory, which has a total trip time of 671.93 days, is in the heliocentric phase of the mission for approximately 130 days outbound and 536 days return.

In order to reduce discrepancies in comparison of data for the two types of measurements, the measurement schedules were pre-set to 1-hour intervals within the Earth or Mars sphere of influence and to 1/2-day intervals during the heliocentric phases.

Initial root-mean-square (RMS) uncertainties for position and velocity were assumed to be 4 n. mi. and 16 fps, respectively. For the sextant measurement, a 10-arc second instrument error, a 100-n. mi. ephemeris error, and observed radius errors of 4 n. mi. and 10 n. mi. for Earth and Mars, respectively, were assumed for the modeling of the total variance of observation errors. Information concerning the modeling of the sextant measurements and the selection of a body sighting schedule can be found in reference 1.

For the range-rate sensor measurements, the sensitivity vector H which relates measurements deviations to state deviations is defined by

$$H^T = \begin{bmatrix} \left(I - \underline{u}_\rho \underline{u}_\rho^T\right) \dfrac{\underline{V}_{vs}}{\rho} \\ \\ \underline{u}_\rho \end{bmatrix}^{6 \times 1}$$

where I is a 3 × 3 identity matrix, $\underline{u}_\rho$ is the 3 × 1 unit vector in the direction of the line of sight to the sun from the spacecraft, ρ is the range, and $\underline{V}_{vs}$ is the 3 × 1 velocity vector of the vehicle relative to the sun.

The covariance matrix of measurement errors for the range-rate sensor measurement reduces to a scalar and is equal to the variance of the instrument making this type of measurement. It is recognized by the author that this is a rather simple error model; however, the problem is approached in this manner because of limited information concerning such an instrument. From information obtained previous to this study, an instrument error of only 0.02 fps was quoted. This value was used in some of the cases presented. However, because of the lack of knowledge of other errors that could possibly be involved in such an instrument's performance and because of the belief that the quoted value is rather small, errors of 0.2 and 2 fps were also used in evaluating the effectiveness of the onboard range-rate sensor measurement.

RESULTS AND DISCUSSION

The results of the study of a range-rate sensor measurement are graphed in figures 1 and 2 in order that comparisons may be made and conclusions may be easily drawn by visual examination of the curves plotted.

All data are plotted against time in days from injection on the outbound leg of the trajectory and from Mars periapsis on the return leg. Since the state uncertainties of principal interest are those at periapsis of the approaching planet, the curves presented are representative of the projected uncertainties to the particular periapsis of interest at all times along the trajectory.

Sextant measurement data, represented by a dashed line, are given in each figure for comparison with that of the range-rate sensor measurements. The uncertainty curves for the sextant measurements are considered representative although a non-optimum star selection technique was used. Also, the uncertainty value curves would tend to be somewhat lower, when within the spheres of influence of Earth and Mars, for measurement intervals of 30 minutes rather than intervals of 1 hour (ref. 2). However, the trajectory phase of particular interest in this study is the heliocentric phase where studies have shown that measurement intervals of less than the given 1/2-day intervals do not significantly affect the uncertainty curve profile. Also, at all times along the trajectory the measurement intervals for the sextant and those for the range-rate sensor correspond directly. Thus it is assumed that the conclusions drawn by comparisons of the curve profiles given for both type measurements would not be significantly altered by a decrease in measurement time intervals, especially until more information concerning an instrument for a range-rate sensor measurement can be obtained.

Figures 1(a) and 1(b) contain altitude uncertainty curves for sextant and range-rate sensor measurements projected to Mars periapsis and to Earth periapsis, respectively. The range-rate sensor data in these curves represent the minimum instrument error of 0.02 fps. Figure 1(a) has a divided scale in order that one may more easily differentiate between the curves within the Mars sphere of influence (MSOI). As can be seen, only sextant measurements are made within the Earth's sphere of influence (ESOI), and the altitude uncertainty projected to Mars periapsis is so large that it is relatively insignificant data at this early time in the trajectory. At the ESOI and the beginning of the heliocentric phase of the outbound leg to Mars, two types of measurements are represented - the all onboard sextant measurement represented by Curve 1 and the all range-rate sensor measurement represented by Curve 2. By inspection of the two representative curves, it can be seen that the range-rate sensor measurement significantly reduces the projected altitude uncertainty early in the mission, then levels off until the MSOI. At approximately 90 days out the sextant measurements, Curve 1, begin producing a greater reduction in altitude uncertainty. This condition can be explained by the fact that sextant measurements tend to give good information of the spacecraft state, thus reducing its estimation uncertainties, when the spacecraft is near a planet to which it is sighting. Therefore, when approaching a planet, better information is produced by the use of the sextant than by the measurement of the rate of change of the line of sight to the sun.

Within the MSOI, Curve 1 is the continuation of the Curve 1 from the heliocentric phase of the trajectory. However, at the MSOI, Curve 2 is continued for two examples. That is, 2(a) represents Curve 2 when sextant measurements are begun at the MSOI, and 2(b) represents Curve 2 when range-rate sensor measurements are continued through the MSOI to Mars periapsis. As is evident, for the outbound leg of the

1975 Mars flyby mission, the three combinations of measurements presented - all sextant, the combination of range-rate sensor measurements during heliocentric and sextant during the MSOI, and all range-rate sensor measurements - produce final effects of approximately the same value. However, for maneuvers early in the mission, it is vital that good information of the state be known at that particular time, thus the earlier the uncertainties can be reduced to low workable values, the better a mission can be performed. Obviously, for this particular example and comparison, the range-rate sensor measurement performance is much better during the major part of the heliocentric phase of the outbound mission leg.

Figure 1(b) contains the continuation from figure 1(a) of the Curves 1, 2(a), and 2(b) through the return leg of the mission from Mars back to Earth. For the return leg, the range-rate sensor measurements produce data which are at all times during the heliocentric phase, up to the ESOI, much better than that produced by the all-sextant measurements. This figure, like figure 1(a), is broken into two major parts. For the return leg, only sextant measurements are made within the ESOI.

In order to observe what the range-rate sensor measurement does to the separate components of position, the RMS uncertainties for the projected altitude, range, and track are presented for the Earth-to-Mars leg in parts (a), (b), and (c), respectively, of figure 2. The all-sextant measurement curve, again represented by a dashed line, is for the same conditions as that in figure 1. Also illustrated in these figures is the effect of the range-rate sensor measurement for different error conditions. That is, curves a, b, and c in all parts of figure 2 represent parallel studies of the range-rate sensor measurement for which the total standard deviation (σ_T) was assigned the values of 0.02, 0.2, and 2 fps, respectively. As can be seen, even with a rather conservative assigned error, the range-rate sensor measurement reduces effectively the uncertainties in all three of the position components.

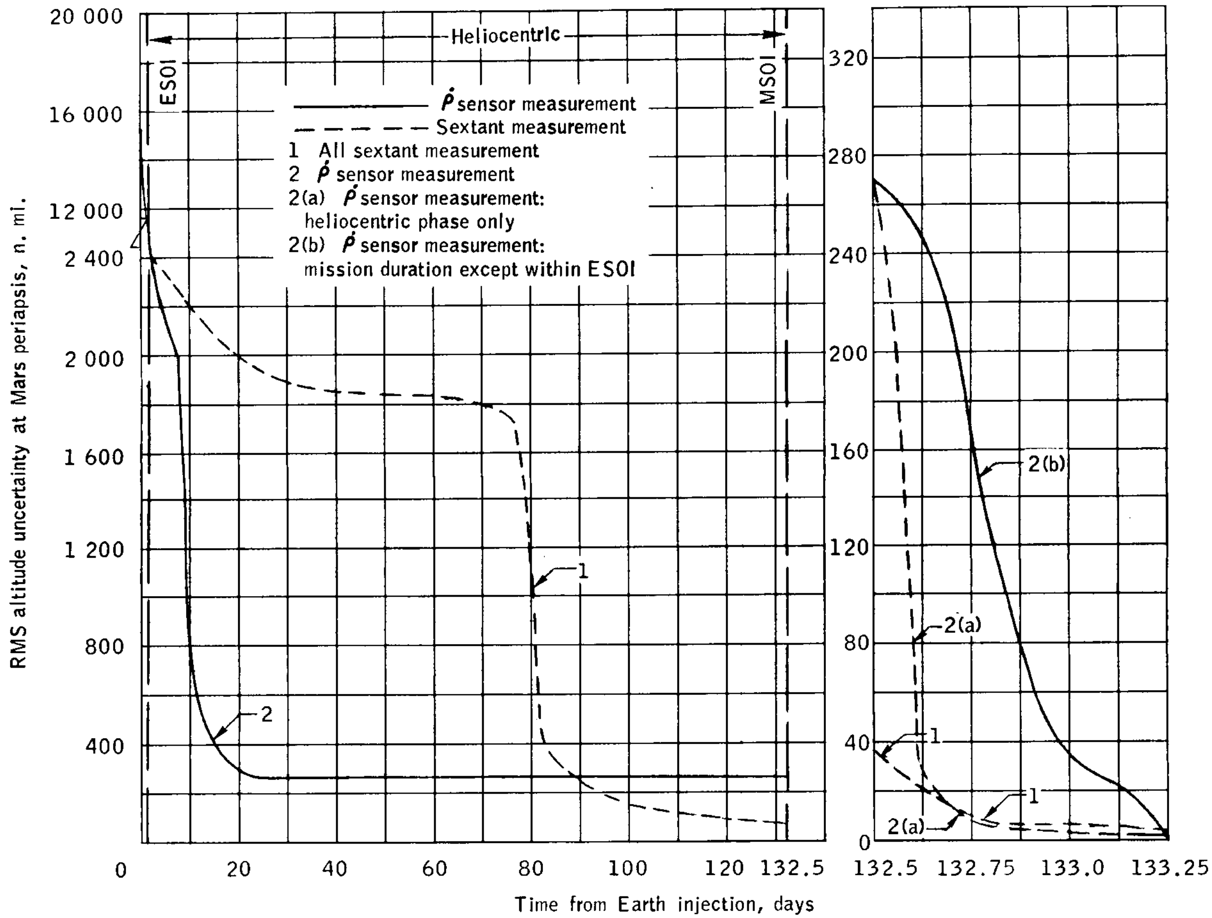
Noticing the obvious increase in the effectiveness of the sextant measurement for reducing the estimated position uncertainties after approximately 80 days out, a case was investigated for which the minimum error range-rate sensor measurements were made during the heliocentric phase out to this point, at which time the navigation measurement was switched to the sextant planet-star measurement. This is illustrated in figure 2 by the Curve a'. For all position error components - altitude, range, and track - this mixture of measurements produced the best results.

As is evident by inspection of the error curves of figures 1 and 2, a type of range-rate sensor measurement is very effective in reducing estimated position uncertainties during the heliocentric phase of an interplanetary mission. Also obvious is that at certain points in a trajectory sextant measurements are more efficient, but these are shown to be better if the uncertainties have been reduced considerably before their initiation.

There are many reasons why early reductions in estimated state uncertainties are needed. Perhaps the most important of these is in estimation of state dispersions which in turn determine guidance fuel budget requirements. Since estimated uncertainties determined by navigation measurements represent a lower bound for the state dispersions, the effectiveness of a guidance system is somewhat dependent on the efficiency of the navigation system. Thus, it is important that an onboard navigation system be able to reduce estimated state uncertainties as early in the mission as possible. Figures 1 and 2 illustrate that this can be done rather effectively with an onboard range-rate sensor type navigation measurement for reasonable errors and rather simple error modeling.

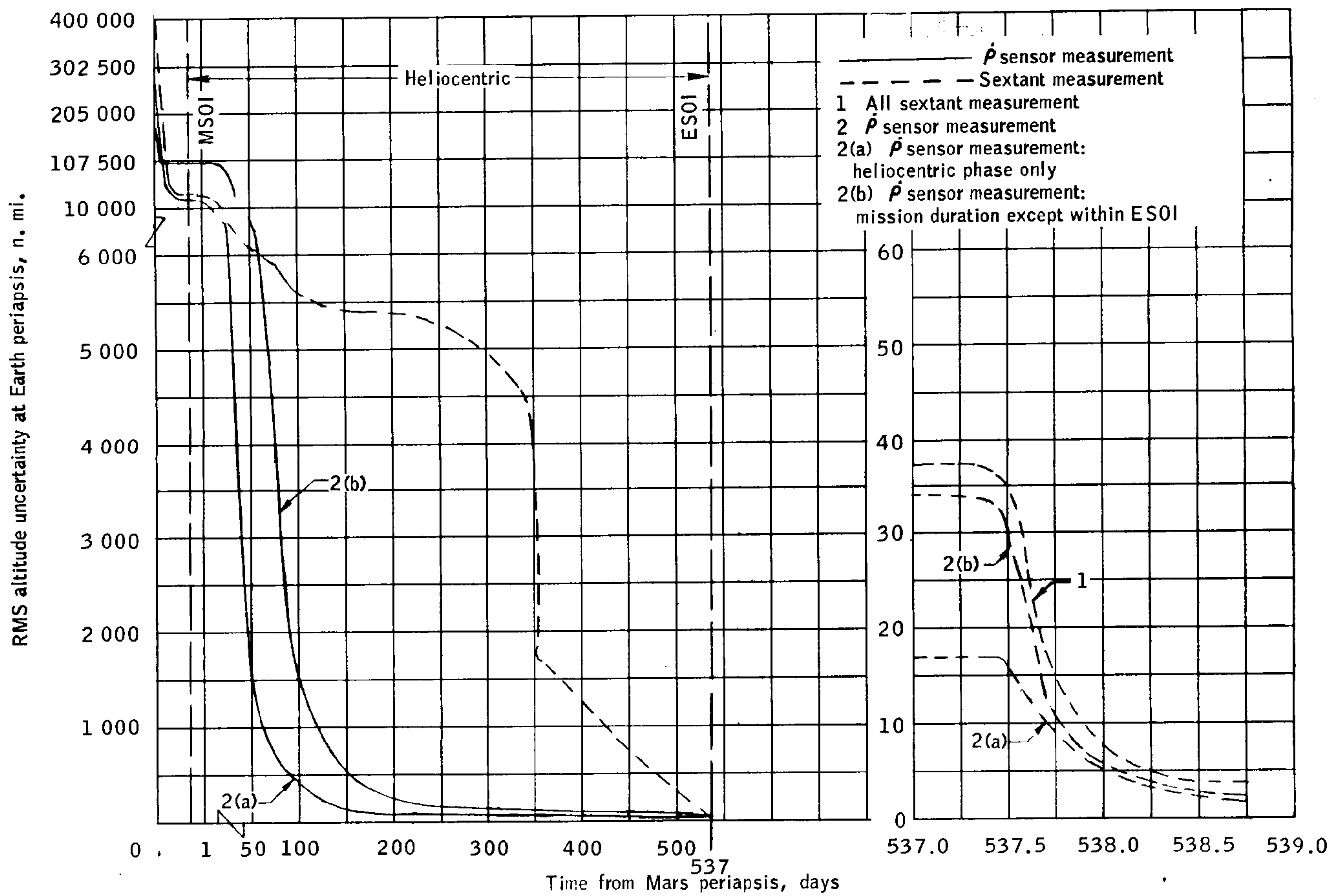
CONCLUSIONS

The effects of an onboard range-rate sensor measurement for interplanetary navigation has been presented. The type of measurement investigated was the rate of change of the line of sight to the sun. The effectiveness of this measurement was investigated for a 1975 Mars flyby mission for the heliocentric phases as well as for the duration of the mission outside of the ESOI. The results of the study indicate that an onboard range-rate sensor measurement is very effective in reducing estimated state uncertainties during the heliocentric phases of an interplanetary mission. The best results obtained for the total mission were for the use of the range-rate sensor measurement during the major portion of the heliocentric period and the sextant measurements for planet approach and within a planet sphere of influence. Various errors were assigned to the range-rate sensor model for the study. It was found that the range-rate sensor measurement was still significantly effective in the reduction of the estimated uncertainties during the heliocentric phase even when assigned rather conservative error values.



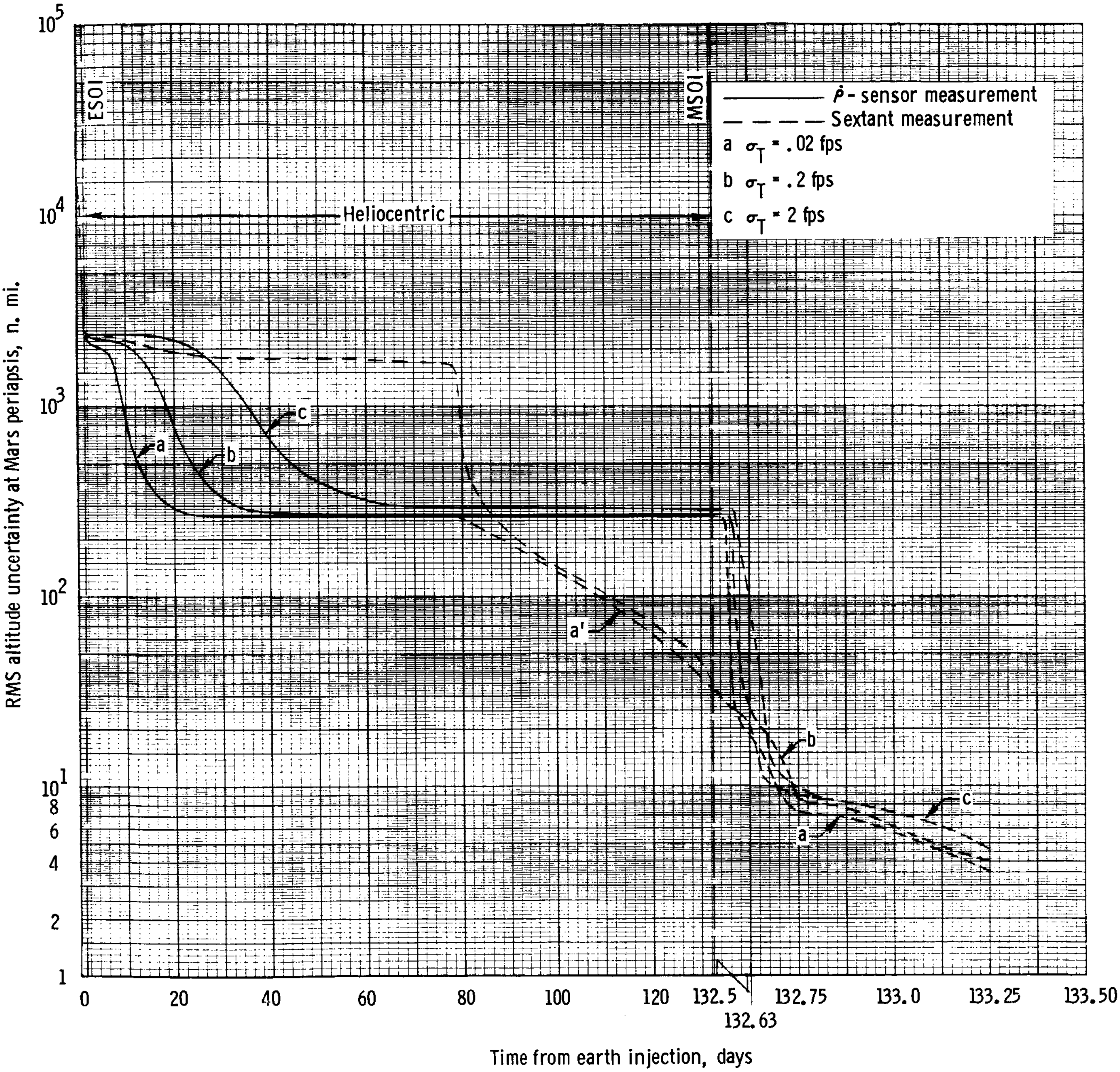
(a) Outbound (Earth to Mars).

Figure 1.- Periapsis altitude uncertainty comparing 10-arc second sextant measurements to .02 fps accuracy range rate sensor measurements.



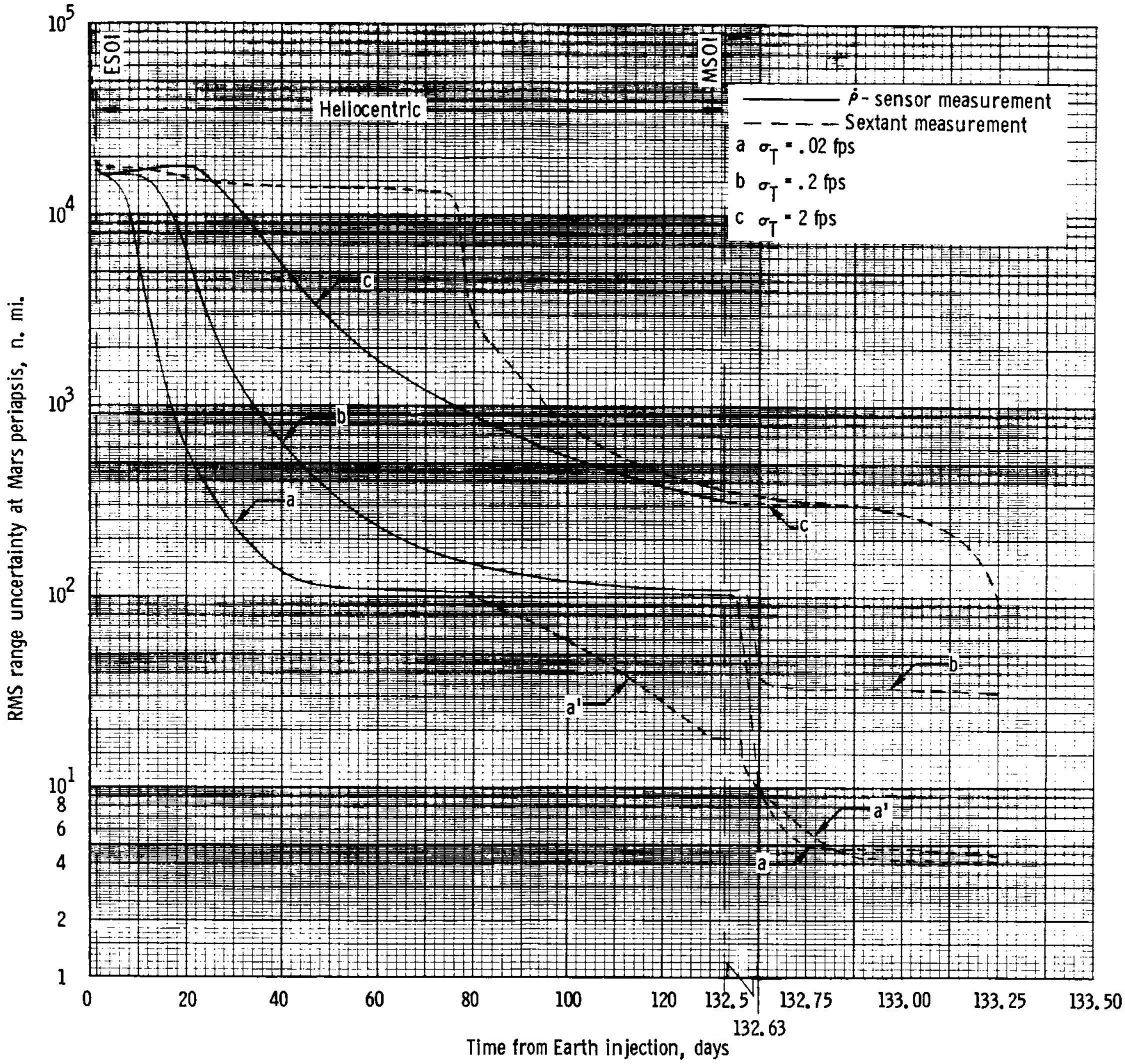
(b) Return (Mars to Earth).

Figure 1.- Concluded.



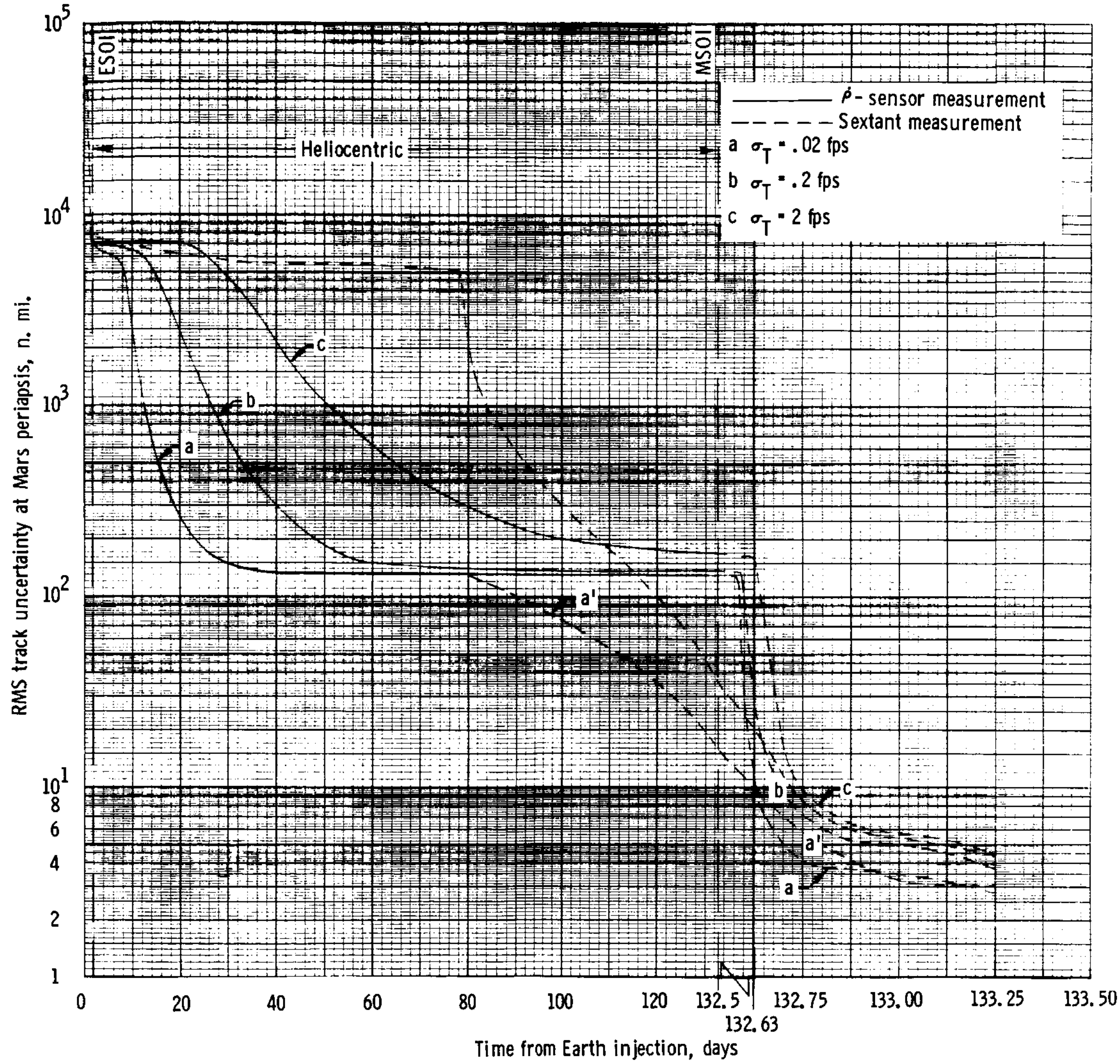
(a) RMS altitude uncertainties at periapsis.

Figure 2. - Mars periapsis position uncertainties for 10-arc second sextant measurements and .02, .2, and 2 fps accuracy range-rate sensor measurements.



(b) RMS range uncertainties at periapsis.

Figure 2. - Continued.



(c) RMS track uncertainties at periapsis.

Figure 2. - Concluded.

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1. Lowes, Flora B.; and Murtagh, Thomas B.: Preliminary Navigation and Guidance Analysis for a 1975 Mars Flyby Mission. MSC IN 67-FM-104, July 26, 1967.

2. Murtagh, Thomas B.; Lowes, Flora B.; and Bond, Victor R.: Navigation and Guidance Analysis of a Mars Probe Launched From a Manned Flyby Spacecraft. No. 67-546. Preprint volume of technical papers presented at AIAA Guidance, Control, and Flight Dynamics Conference, Huntsville, Alabama, August 14-16, 1967.